SUBMARINE LANDSLIDES ON THE US CONTINENTAL SLOPE: EFFECTS ON A SEARCH FOR THE USS *ALLIGATOR*

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ABSTRACT

One of the likely resting places of the lost US Navy submarine USS *Alligator* is on the continental slope of the US Atlantic continental margin. This area of the sea floor contains many significant geological features, with submarine landslides numbering among the most common. The presence of both large and small submarine landslides could have considerable effects on any search undertaken to find the lost submarine. Possible considerations include: rough bottom conditions resulting in increased acoustic reflectance, entrained gas hydrates that cause acoustic anomalies, vast debris fields of large boulders and clasts that could cause false target identification, and exaggerated vertical relief caused by headscarps. All of these factors cause complications that would not normally be expected on the open continental slope.

INTRODUCTION

The USS *Alligator* was a prototype US Navy submarine that was lost at sea on April 2, 1863, somewhere offshore Cape Hatteras, North Carolina. The USS *Sumpter*, a merchant steam vessel towing the *Alligator*, encountered a violent storm and was forced to cut the tethered submarine loose to survive the gale force winds (Terrell and Weirich, 2002). Although the diameter of the possible resting place of the *Alligator* is in excess of one hundred nautical miles (figure 1), the prevailing currents at the time and place of the *Sumpter's* last fix make it likely that the submarine sunk somewhere over the continental slope or rise off of North Carolina (Maloney, 2003). If a search and recovery effort is to be attempted, serious consideration of the ocean floor features in this area will be necessary.

Along with vast systems of canyons, the predominant ocean floor features on the US Atlantic continental slope are submarine landslides. Also called "mass movements", submarine landslides are the downslope movement of sea floor sediment in large masses caused by stress loading on the sea floor sediment beds (Lee and others, 1993). Some of these landslides can be massive when compared to similar terrestrial events. Submarine landslides on continental slopes have been measured in excess of 400 kilometers long and covering areas of over 19,000 square kilometers, roughly the size of the state of New Jersey (Booth and others, 1993). The size of these features, along with their abundance on the continental slope, require considering when planning a potential search for the *Alligator*. The *Alligator* is only 15 meters long, and about 2 meters in diameter (Maloney, 2003). Since even a large wreck would be affected by the massive landslides present on this region of the continental slope, the considerations for a small object like the *Alligator* are even more complex.

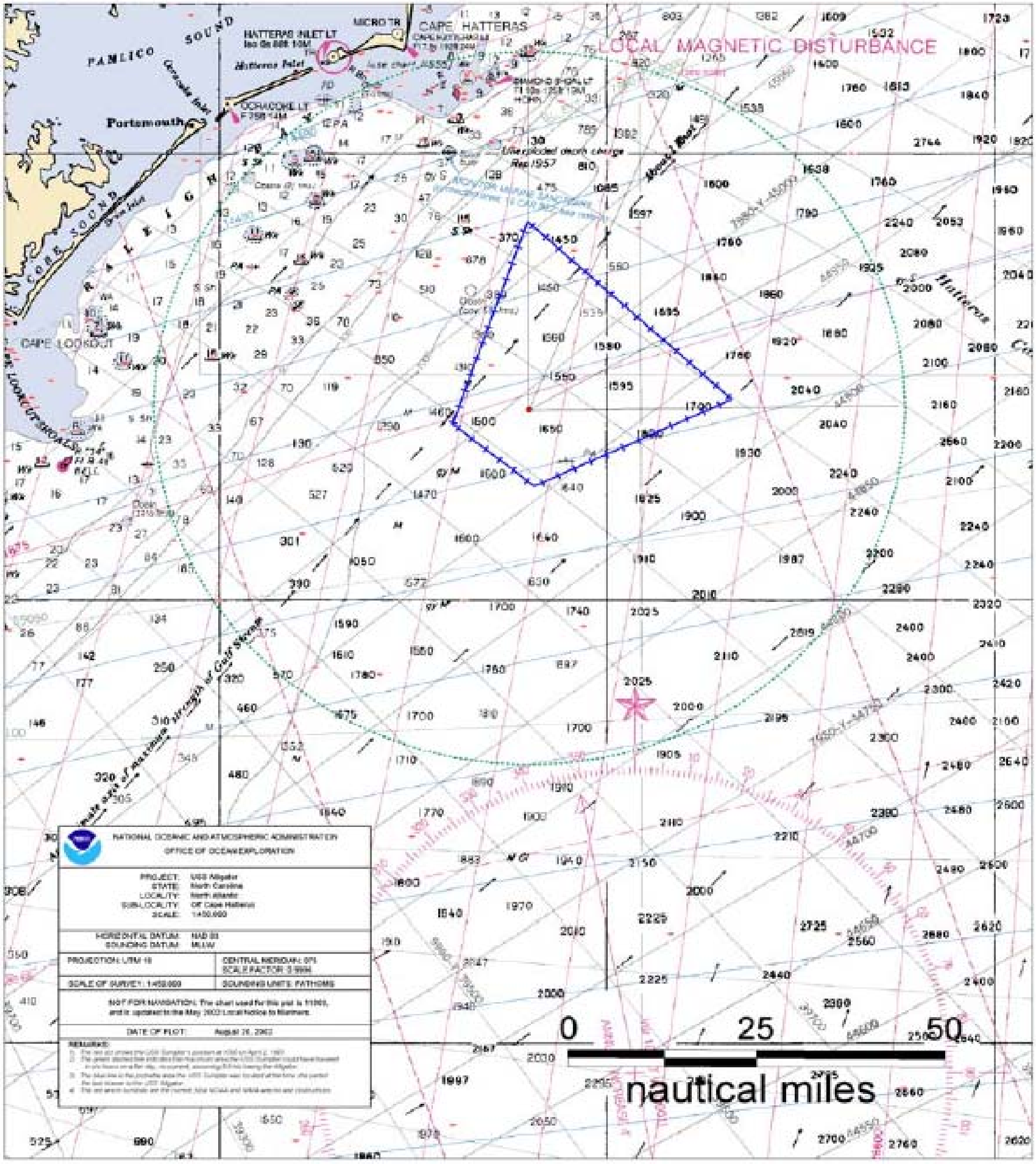

Figure 1: Estimated position circle of resting place of USS Alligator based upon last known fix of USS Sumpter on April 2, 1863 (Terrell and Weirich, 2002). The submarine could have drifted a significant distance outside of this circle due to its watertight condition when cut loose. The blue trapezoid represents the most likely area where the Alligator was cut loose.

CHARACTERISTICS OF THE CONTINENTAL SLOPE ENVIRONMENT

The Atlantic continental slope extends from the edge of the continental shelf, beginning at water depths of between 75 and 200 meters, and is bounded by the continental rise at depths of approximately 2000 meters. The slope angle may be as low as 1 to 2 degrees, or as high as 15 degrees, but averages about 10 degrees. Systems of submarine canyons dominate the terrain of the ocean floor on this slope, along with many submarine landslides (Booth and others, 1993). The most accurate sea-floor imagery of this area was obtained by the GLORIA (Geological Long-Range Inclined Asdic) towed side-scan sonar vehicle (figure 2). A 1991 GLORIA survey revealed hundreds of submarine landslides covering the Atlantic continental slope, not limited to any specific areas or in any sort of uniform distribution by depth or slope angle (Booth and others, 1993).

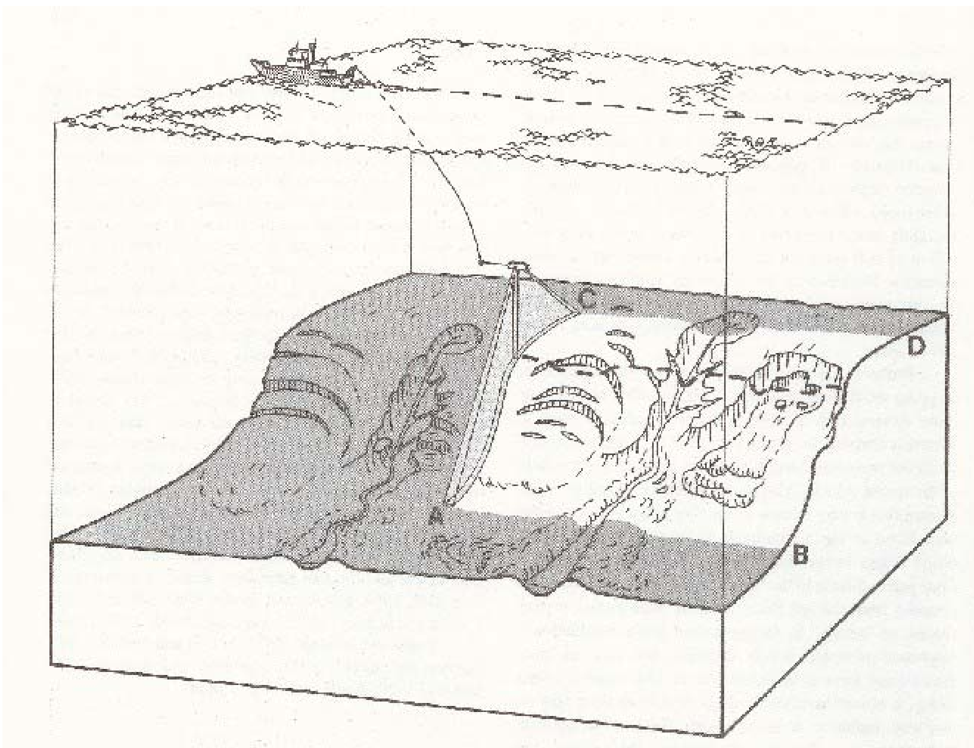

Figure 2: A simple depiction of the operation of a side-scan sonar vehicle like the GLORIA over a continental slope environment (Lee and others, 1993).

Submarine landslides tend to occur in areas where there are thick beds of soft sediment, relatively steep slopes, and high environmental stress loads (Lee and others, 1993). The sediment beds on the continental slope consist mostly of 200 to 300 meters of packed mud made up of mostly silt and clay (Booth and others, 1993). Environmental stresses are also high in this area. Since slope angles of 15 degrees and less make the bottom statically stable, the stresses that cause mass movements of sediment are usually large scale transient forces. Common examples of transient stresses include seismic activity on the bottom, and storm waves created by seasonal hurricanes and tropical storms. The passive Atlantic seaboard margin is still seismically active, and evidence reveals earthquake loading as the main cause of landslide causing slope failure in this area. Storm waves also provide a major cause of slope failures in some continental slope settings but the water depth over the slope in this area makes them much less of a factor than seismic events (Normark and others, 1993). The combination of thickly packed, fine grained sediment, significant environmental stress loading, and the previously mentioned average slope angle of 10 degrees make the US Atlantic continental slope a region where some of the largest and most spectacular landslides known to science have occurred (Lee and others, 1993).

CHARACTERISTICS OF SUBMARINE LANDSLIDES ON THE US ATLANTIC CONTINENTAL SLOPE

The search area of the probable resting place of the *Alligator* contains almost all of the different general types of submarine landslides known to geologists, and these slides have an extremely wide range of sizes, area covered, and effect on the sea floor downslope (Booth and others, 1993). Nevertheless, extensive study of the landslides large enough to be detected using the available GLORIA data has determined some typical statistical values.

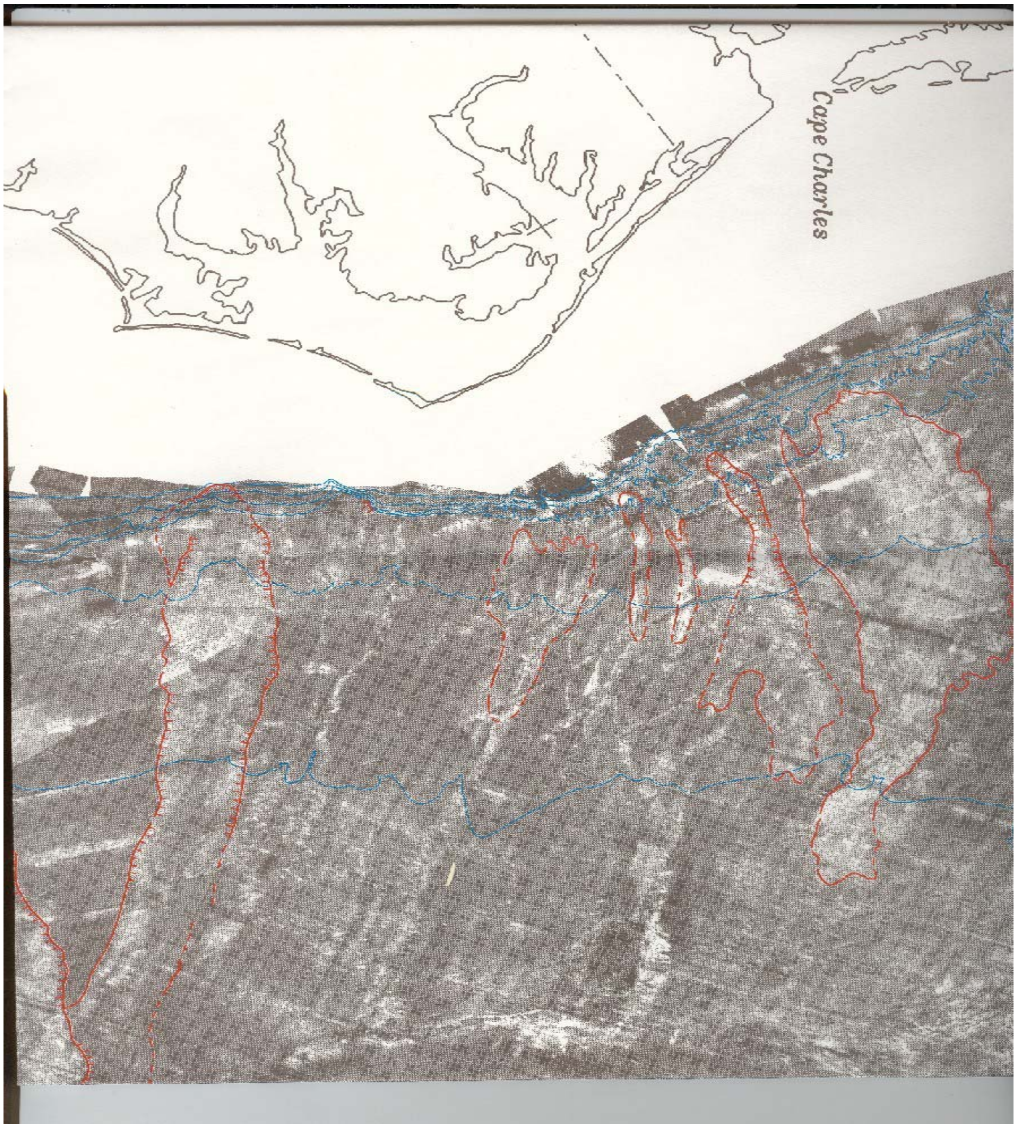

Figure 3: GLORIA imagery off the continental slope off of North Carolina annotated to show large submarine slope slides, which are outlined in red (Booth and others, 1993).

When considering this data, it is important to realize that the coverage of study, and thus the accuracy of the data, is highly biased by the interests of oil and gas companies that have focused on promising sites (Booth and others, 1993). McAdoo and others (2000) also hypothesize that many smaller landslides that elude the resolution of the GLORIA data may be present on the slope. Figure 3 shows the GLORIA bathymetry data on the continental slope off of North Carolina. Although submarine landslides occurred at all depths on the continental slope, an average depth of 800 to 1000 meters was the favored origin. Landslides in this area range from 0.3 to 380 kilometers in length, with an average length of 2 to 4 kilometers. Width ranges between 0.2 and 50 kilometers, with an average value of 1 to 2 kilometers. Thickness ranged between 10 and 650 meters, with values ranging so far that no reasonable average could be reached. Area covered by the slides ranged from less than 0.1 square kilometers to over 19,000 square kilometers, but most covered 10 square kilometers or less. Average slope angle at point of origin was 4 degrees or less (Booth and others, 1993). Headscarp height at the vertical wall of the scar-like depression left behind by the slide varied between 10 meters and 400 meters, though it must be noted that 10 meters is the minimum vertical resolution of the NOAA gridded bathymetry (Mcadoo and others, 2000). Typical landslide data is presented in Table 1.

Table 1: Typical characteristics of submarine landslides on the US Atlantic continental slope and rise (Booth and others, 1993).

Characteristic	Average	Maximum observed	Minimum observed
Length	2-4 km	380 km	0.3 km
Width	1-2 km	50 km	0.2 km
Thickness	N/A	650 m	10 m
Area	10 km^2	19,000 km^2	<0.1 km^2
Depth of Origin	800-1000 m	N/A	N/A
Slope angle	4 degrees	15 degrees	<1 degree
Headscarp height	N/A	400 m	10 m

NON-TYPICAL (MASSIVE) LANDSLIDES

The average values presented above are reasonable for considering the effects of submarine landslides on the ocean floor in the vicinity of the prospective search area, however, this area of the continental slope contains a significant number of non-typical landslides which have a markedly different effect on the sea floor. These non-typical landslides differ mainly in the size of the geological phenomenon and the amounts and type of sediment displaced. The open continental slope off of the central US contains enough of these massive atypical landslides to warrant the attention of anyone hoping to search the sea floor in this region.

One of the best studied examples of such a landslide is the Cape Fear landslide, a truly massive downslope movement originating on the continental slope off of Cape Fear, North Carolina (Popenoe and others, 1993). The Cape Fear slide originated at 2,600 meters of depth and extends over 400 kilometers down the slope, terminating a significant distance out onto the abyssal plain at a water depth of 5.4 kilometers. The headscarp is over 50 kilometers long and 120 meters high. The slide created an intricate system of scrunched carpet-like slumps over 40 kilometers downslope from the headscarp (Popenoe and others, 1993). Such a large landslide is capable of moving or exposing extremely large sediment, including boulders nearly 10 meters in diameter. Slab slides such as the Cape Fear slide leave a massive debris sheet behind, creating rough ocean floor and local vertical relief on the order of several meters (figure 4).

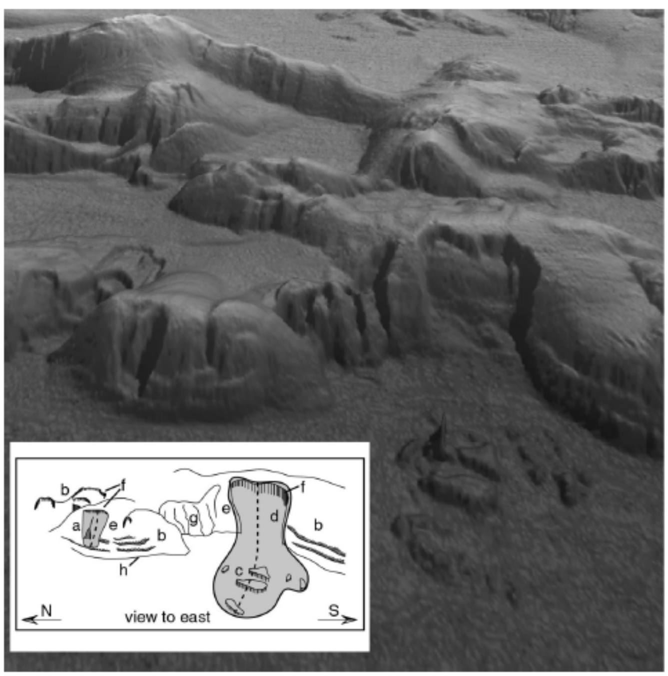

Figure 4: Three dimensional image of the bottom conditions left in the wake of a large submarine slab slide off of Oregon. Similar vertical reliefs and features exist on the US Atlantic continental slope (Mcadoo and others, 2000). Note the nearly vertical headscarp (f) and the massive sediment clasts (c) visible downslope.

Core samples from this slide show that debris typically is made up of clayey silt with sharply angular clasts of broken up older strata (O'Leary, 1991). Seismic stress alone seldom causes such a massive slide, and the Cape Fear slide is no exception to the rule. This slide, along with many of the other larger than normal submarine landslides, was caused by stress loading on the sediment due to entrained gas hydrates in the sediment bed. The ice-like trapped gas causes great accumulated stress on the sediment bed, eventually causing catastrophic failure (O'Leary, 1991). One reason that this slide is so well studied, besides its massive size, is that the remaining trapped gas in the debris causes higher than expected acoustic returns. This makes slabs caused by such a mechanism stand out against the non-disturbed, gas free sediment around the slide area, and thus the boundaries of the slide and scarp are easily viewed (Popenoe and others, 1993).

CONSIDERATIONS FOR A SEARCH ON THE CONTINENTAL SLOPE

Understanding the characteristics and effects of submarine landslides, while obviously interesting to geologists, also proved necessary to conduct an effective search on the continental shelf. Though the silt and clay dominated sediment of the continental shelf would seem to offer an excellent backdrop against which to search for the acoustically reflective *Alligator*, debris fields left by landslides exhibit surprisingly high acoustic signatures due to bottom roughness (Mcadoo and others, 2000). This may be a desirable characteristic when studying submarine landslides in their own right, but will not be helpful when searching for a small submarine against a backdrop already littered with submarine canyons. The characteristic roughness of the bottom on the Atlantic slope is shown in Figure 5.

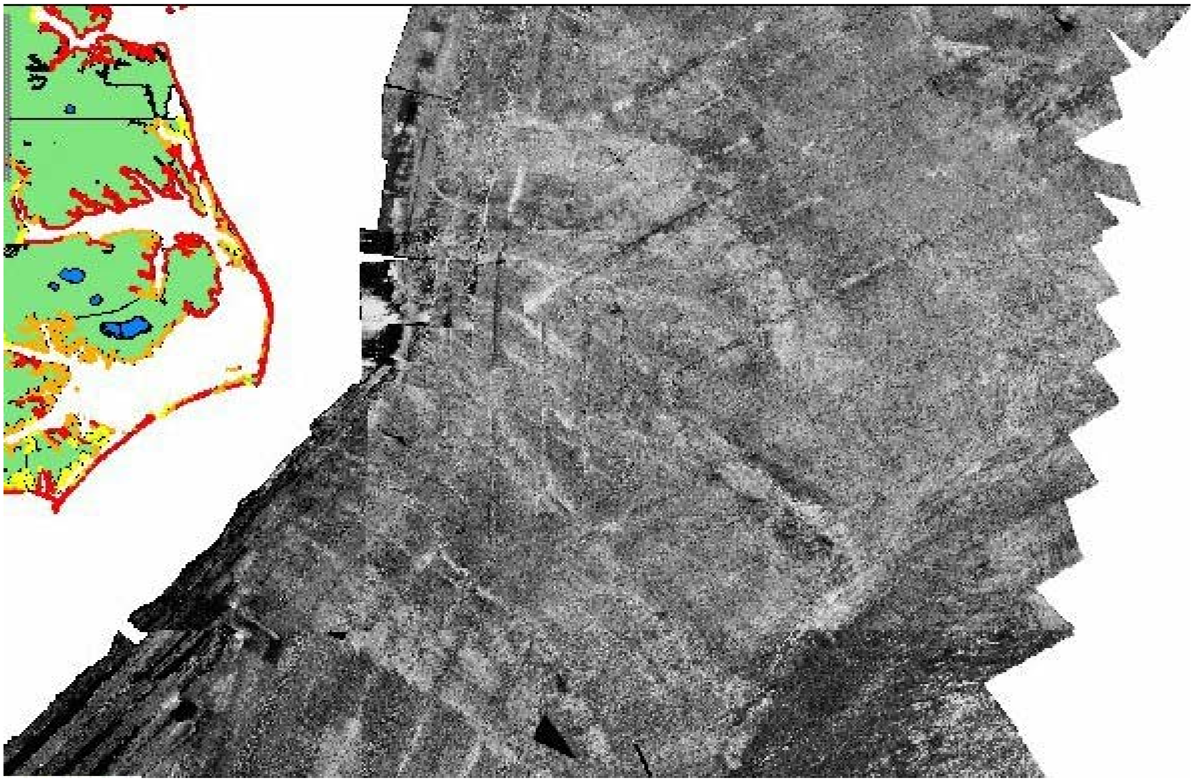

Figure 5: USGS GLORIA imagery of the ocean floor on the US Atlantic continental slope off of North Carolina. The lighter areas are more acoustically reflective, indicating a hard or rough bottom, both characteristics of submarine landslides. Note the general roughness and complexity of the bottom here even on a large scale (USGS, 2004).

Larger non-typical landslides present an even greater obstacle. Bottom conditions on these massive debris fields are very rough and very acoustically reflective. Trapped gas hydrate causes even more trouble, as acoustic scans of these areas reveal large "amplitude anomalies" of highly reflective free gas (Popenoe and others, 1993). In addition, the large debris fields left behind by slab slides can contain boulders potentially the same size as the *Alligator* itself. Both the anomalies and debris will have to be considered to prevent wasted search effort on identifying false targets. The local vertical relief left in the path of these massive slides would also complicate a potential search, it would be much simpler to consider a smooth bottom, as would be expected on the undisturbed continental slope (Popenoe and others, 1993).

Although not very likely, it is possible that the *Alligator* could have been covered, or rolled downslope, by a submarine landslide in the 141 years since it was lost. It would be much simpler to determine the likelihood of this occurrence if the ages of landslides were easier to determine. Unfortunately, most of the medium to large size submarine landslides (practically all of the slides large enough to register on the GLORIA data) produce debris fields that conform to the sediment bedding around them, making it difficult to determine the age of the slope failure (O'Leary, 1991). To date, the ages of most submarine landslide slope failures off of the US Atlantic coast remain unknown (Lee and others, 1993). Despite this obstacle, we do know that seismic events produce accumulating stresses that are the leading cause of submarine landslides on the continental slope. Since their emplacement in the 1970's, underwater seismic sensors have recorded many seismic tremors off Cape Hatteras (Booth and others, 1993). Having detected the leading cause of submarine landslides so many times in recent years in this area, it is reasonable to assume that landslides, at least the smaller typical variety, have occurred since the loss of the *Alligator*. Though large scale landslides have been detected in the years since the loss of the *Alligator*, none are in an area that would likely be the resting place of the submarine (Maloney, 2003). If the *Alligator* were caught in a small submarine landslide, it could have been covered wholly or partially by sediment, since even the smallest typical landslides leave behind debris fields 10 meters thick or more (Booth and others, 1993). It is, however, unlikely that a typical landslide would have been able to push or roll the submarine any significant distance downslope, as only the largest slab slides move boulders approaching the dimensions of the *Alligator* (O'Leary, 1991). These possibilities are worth consideration, but it is more likely that the *Alligator* is resting on the debris field of a much older landslide.

CONCLUSIONS

Any search of the sea floor on the continental slope will encounter many difficulties, water depth and the vast networks of submarine canyons not among the least of them. Sediment type, as discussed by Maloney (2003), is an important factor when considering the acoustic reflection properties of the bottom and the potential search difficulties resulting from disturbed sediment in the water column, but even more important is the large scale roughness of the bottom and the presence of large vertical features and boulders associated with submarine landslides. The rough bottom conditions, large vertical headscarps, acoustic anomalies, general high acoustic reflectivity, and potential false target bottom features, all must be carefully considered when planning a search of the proposed area. The fact that the Alligator could have been partially or completely covered by a landslide only complicates matters further. When considering these facts, it quickly becomes evident that a search would be much easier if the *Alligator* had settled on the continental shelf, as was the case with the USS Monitor.

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